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The Hygroscopic Capacity of Wool in Different Forms and its Dependence on Atmospheric Humidity and other Factors

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The Thermodynamics of Water Absorption by Textile Materials

By
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THE HYGROSCOPIC CAPACITY OF WOOL IN DIFFERENT FORMS AND ITS DEPENDENCE ON ATMOSPHERIC HUMIDITY AND OTHER FACTORS

By S. A. SHORTER, D.SC., and W. J. HALL, B.SC., A.R.C.S.

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SUMMARY

The regain* of wool in different forms (scoured wool, top &c.) has been measured in atmospheres of relative humidity ranging from 44% to 90% at a temperature of 72° F. Different qualities of wool were investigated (also mohair). It was found that the "quality" of the material had very little or no effect on the regain. One of the qualities (64's Cape wool) showed perhaps a significant divergence from the other four qualities. Thus at 90% humidity the regain of the Cape top was 21·30% while those of the other four were 22·25%, 22·14%, 21·90% and 22·00% respectively. It would not be safe, however, to generalise from this about the regain of Cape wools. The difference between the Cape tops and the others is small enough to be accounted for by some difference in treatment (*e.g.* in drying after back-washing).

Different forms of the same material showed in certain cases small but unmistakable differences. Yarns and tops gave the same results. Noils were found to be less hygroscopic owing to the presence of foreign matter.

Oil was found to diminish the regain of wool. The oil apparently exerts practically no effect on the moisture-absorbing power of the wool, producing a diminution of the calculated regain merely by loading the material with a non-hygroscopic substance.

Pieces were found to show wide variations of regain. This result is to be expected owing to the drastic nature of certain finishing processes.

From the average results for different materials, the atmospheric humidities corresponding to the regain standards have been calculated. These humidities vary for the different standards. Thus, if a top in oil be

* In studying this paper, readers who are not entirely familiar with such terms as "regain," "hygroscopic capacity" &c. are referred to the explanatory note at the end.

stored in an atmosphere which will bring it to the standard regain of 19%, then a dry top in the same place will come to a regain of about 19½%, though the standard for dry tops is 18¼%.

Measurements have also been made on samples exposed to ordinary indoor and outdoor atmospheres. The standard for tops in oil was found to be practically equal to the yearly mean of the outdoor regain of the samples of tops, while that for cloth was found to be equal to the yearly mean of the indoor regain of the sample of cloth.

As a sample of the information that can be obtained from this paper, it may be stated that the average regain for the year in an ordinary living room is—

15·5% for Scoured Wool.
15·5% for Tops or Yarn in Oil.
16·0% for Dry Tops or Yarn.
15·0% for Noils.
15·0 to 17·0% for Cloths.

I.—INTRODUCTION

In spite of the commercial importance and the scientific interest of the subject of the absorption of moisture by textile materials and other similar colloids, the information at present available on the subject is extremely small. The present paper is the beginning of an attempt to remedy this deficiency in the case of wool.

The object of the present paper is a study of the hygroscopic capacity* of different kinds of wool in the forms in which it is met in the industry. The material used in the investigation has received the ordinary trade treatment and the results may therefore be regarded as representing the properties of the ordinary commercial products. Apart from its practical bearing, such a starting point has proved of value from a scientific standpoint. A study of the differences shown by ordinary commercial samples of wool and the correlation of these differences with such information as was available about the treatment of the samples, gives promise of leading to results of interest in the general theory of hygroscopic colloids.

The scope of the present paper is, however, limited to ordinary commercial material. The observations recorded relate in the main to samples exposed in a room whose humidity and temperature were controlled to a high degree of accuracy. Special precautions were taken with regard to what is always the most difficult measurement in work of this kind, viz., that of the atmospheric humidity. A given humidity was maintained for a lengthy period—one to three weeks. Humidity measurements were made every day, and several times a day, by one or other of several methods. In addition an automatic recording device for humidity and temperature was fitted up. This recorded continuously—day and night—the state of the room and was a valuable check on the working of the different controls.

Section II. contains an account of the method of experiment considered under the headings—(*a*) Collection of Samples, (*b*) Temperature Control, (*c*) Humidity Control, (*d*) Humidity Measurement, (*e*) Weighing of Samples, (*f*) the Estimation of the Dry Weight.

The main experimental results are tabulated in Section III. and discussed in Section IV. The most important conclusion arising from this discussion is that the hygroscopic capacity stands in no relation to the "quality"—an

* *i.e.* Moisture-absorbing power or power of acquiring "regain."

80's Botany not differing appreciably from a Yorkshire Hog wool of about 40's quality, or even from mohair. The form of the wool (wool, top, yarn &c.) is found to influence the regain to a slight but quite unmistakable extent.

All forms of wool subsequent to the unscoured material, and previous to that of partly finished or finished cloth, exhibit a considerable uniformity in spite of the diversity of material. Finished pieces, on the contrary, show a remarkable lack of uniformity.

In Section V. it is shown that the effect of oil is to diminish the hygroscopic capacity. By means of specially designed experiments it is shown that the magnitude of this effect is approximately such as would correspond to the loading of the wool with an inert non-hygroscopic substance. The oil, in fact, neither absorbs much moisture nor affects the moisture absorbed by the wool.

Section VI. deals with the question of the relative humidity necessary to give the different standards of regain (19% for tops in oil, 16% for cloth &c.).

In Section VII. are given the results of a series of observations on material exposed to ordinary atmospheres (uncontrolled), with a view to seeing what is the natural regain of wool, outdoors and indoors, on an average throughout the year.

Section VIII. shows that raw or unscoured wools are very irregular in regain owing to variation in the amount and kind of impurity, grease, sand &c.

II.—GENERAL METHOD OF EXPERIMENT

The Collecting of the Wool Samples—In the case of a particular kind of wool in different forms, the samples of each form (raw wool, scoured wool, top &c.) were collected from the same run in lots of a few pounds. The actual samples tested in the Humidity Room were taken from these larger samples and weighed approximately half a pound. The looser forms (*e.g.* raw wool, noil &c.) were kept in copper cages of known weight; the more coherent forms (*e.g.* top, yarn &c.) were looped up in bundles and hung up by means of copper wire.

Temperature Control—The temperature was controlled by means of a large mercury thermometer containing about 30 lb. of mercury. This had a cylindrical bulb, 25 in. long and $1\frac{3}{4}$ in. in diameter. It was mounted with the axis of the cylinder at an angle of about 30° with the horizontal. The stem, which was vertical, consisted of a short length of wide capillary tube. The rise (or fall) of the mercury made (or broke) a low voltage circuit which broke (or made) the high voltage of an electrical heater. The temperature of the Humidity Room was kept at 72° F.

The Humidity Control—The air of the room was circulated by means of a fan through a heating chamber (containing the above-mentioned electrical heater) and through either a drying or a humidifying chamber. The two valves which opened and closed these alternative paths were controlled by means of a hygrometer placed in the middle of the humidity room. This hygrometer consisted of a piece of cloth which registered changes of humidity by changes of weight. Such a piece of cloth[1] though perhaps open to objection as a hygrometer for general use has been found to be very useful as a method of control. The control cloth was hung on the arm of a balance which operated electrical contacts which actuated electro-magnets to open or close the valves. When the cloth was too heavy the motion of the balance

pan closed the circuit of the magnet which lifted the valve of the drying chamber. When the cloth was too light, the valve of the humidifying chamber was opened in a similar manner. When the cloth was exactly balanced and both valves were therefore closed, the pressure generated by the fan opened a flap-valve which allowed the air to circulate through a third path.

In the drying tower the air was dried by means of crude calcium chloride. In the humidifying tower the air passed between sheets of calico which were kept wet by means of a supply of warm water which was allowed to trickle down them.

In this method the atmosphere is controlled so as to fluctuate in humidity within more or less narrow limits about that necessary to give a definite regain in the control cloth. The amplitude and period of these fluctuations depend upon a number of factors. It is evidently desirable to have the control cloth in as open a form as possible and well exposed to the air of the room. At present the control cloth consists of two sheets 20 in. by 26 in., 7 in. apart, hanging in a vertical plane parallel to the general direction of the air current.

If the control cloth changes in hygroscopic capacity with the course of time there will be a change in the controlled humidity corresponding to any given cloth weight. We have found that there is no perceptible change in three weeks (the maximum period of maintenance of the humidity at any one value). Any slower change is of no importance since the humidity is measured independently, so that it would not matter if the same cloth weight gave a different humidity six months or a year later.

A much more serious source of error is the inequality of temperature in different parts of the room. The method of control maintains a uniform *partial pressure* of water vapour throughout the room. Now the *relative humidity* in any part of the room will be inversely proportional to the saturation partial pressure at the temperature of that part. Since the saturation partial pressure diminishes about 3% for every 1° F. fall of temperature, it is evident that uniformity of temperature is of supreme importance.

The distribution of temperature was therefore carefully studied and finally certain arrangements regarding the air circulation, lighting and storage of samples were fixed upon as giving the best results. The lights were arranged along the west wall of the room (one of the short walls).* The incoming current of air was directed towards this wall through openings in a trunk placed near the ceiling level about five feet from the wall. The air was withdrawn near the floor level by means of a trunk along the east wall. The samples were stored in the part of the room between the east wall and the inlet trunk. They occupied a volume bounded roughly by vertical planes two feet from the north, east and south walls and the inlet trunk, and horizontal planes one foot from the ceiling and four feet from the floor. It was proved by measurements of temperature, humidity and regain, that within this region the degree of uniformity was perfectly satisfactory. These final arrangements were arrived at after a lengthy series of observations extending over about 18 months, and it may safely be said that they have resulted in a degree of accuracy of control of humidity and temperature never previously obtained in such a large room.

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* The room is a cellar 20 ft. by 12½ ft.

Humidity Measurements—The accurate determination of the atmospheric humidity is the crux of the whole experimental work. Six different methods of humidity determination were adopted. These were—

(1) The ordinary wet and dry bulb hygrometer.
(2) The ventilated wet and dry bulb hygrometer.
(3) The single absolute hygrometer.
(4) The double absolute hygrometer.
(5) The dew-point hygrometer.
(6) The glycerine-refractive-index hygrometer.

The last method was valuable for studying the variation of humidity in different parts of the room, rather than for obtaining absolute values. A few drops of glycerine solution (adjusted to near the final equilibrium concentration) were placed in Petri dishes in different parts of the room and tested after a few days.

A continuous record of both temperature and humidity was obtained by means of thermo-couples connected to mirror galvanometers in an adjacent cellar. For the temperature record one junction was exposed to the air of the room and the other placed in a vacuum flask filled with water. The electromotive force of this pair of junctions is obviously proportional to the deviation of the temperature of the room from its mean temperature. For the humidity record the two junctions were arranged to form the two "bulbs" of a wet and dry bulb hygrometer.

The records were made photographically in the usual manner. A sheet of bromide paper was mounted on a drum driven by clockwork. On this were focussed the spots of light from the mirrors of the two galvanometers. On the same paper was also obtained a record of the working of the controls. Incandescent lamps were placed in parallel with the electro-magnets working the two valves, and with the electric heater, and arranged so as to record a line on the bromide paper. A sample record is shown in Fig. 1. The sheet of bromide paper has been mounted and the temperature, scale &c. marked on the mount. In general, the automatic record was used merely as a check on the efficient working of the controls and not for the actual measurement of the humidity.

Readings of the ordinary and the ventilated wet-and-dry bulb hygrometers were taken several times a day. Measurements with the dew point and absolute hygrometers were taken a few times during a run. The different methods were in close agreement (see Appendix A).

The Method of Weighing—The samples were weighed to 0·01 grm. on an ordinary balance sensitive to 0·005 grm. They were weighed either every day or on alternate days. The order of weighing the samples was varied from day to day, and occasionally a sample was weighed at the beginning of a series of weighings and again at the end, with the object of discovering whether or not the presence of an observer had any effect. It was found that the samples did not show any variation in weight from this cause. Before altering the weight balancing the control cloth, it was made certain that the samples had attained a constant weight.

The final regains as determined may be regarded as correct and within 0·1% on the dry weight of the cloth (see Appendix B).

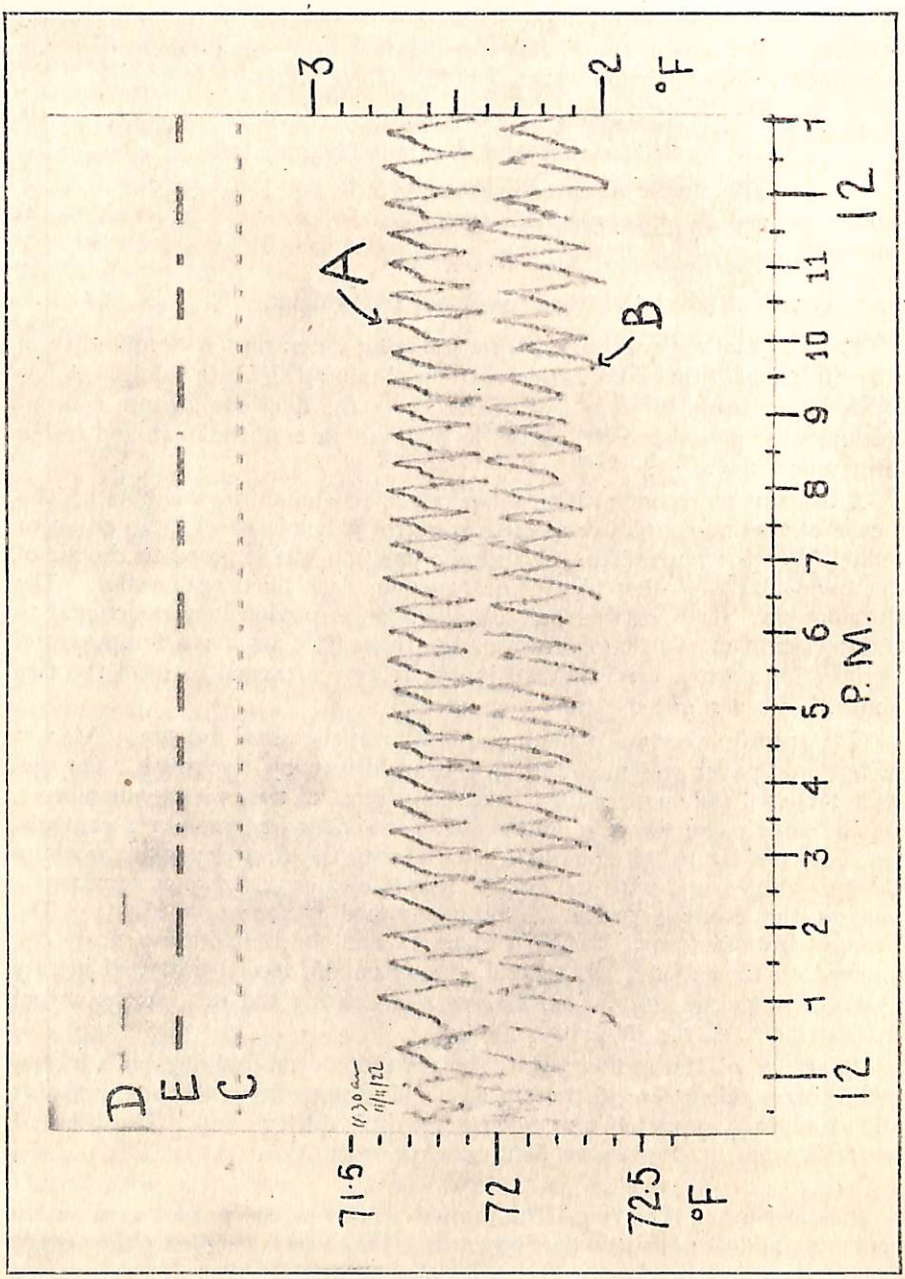

FIG. 1

A—Bulb-difference record (scale on right edge).
B—Temperature record (scale on left edge).
C—Humidifying tower record (mark=tower in; blank=tower out).
D—Drying tower record (mark=tower in; blank=tower out).
E—Heater record (mark=heater on; blank=heater off).

Note—Since at this high humidity the humidifying tower has to be fed with hot water, its cutting in and our produces fluctuations of temperature, which are superposed on the slower fluctuations due to the cutting in and out of the electrical heater.

Actual Size of Record—The bromide paper is 6 in. wide, and fits on a drum of 6 in. diameter.

The Estimation of the Dry Weight—The dry weight of each sample was determined by drying out a portion (and in some cases the whole) of the sample in a Heal oven at the end of the series of observations. Comparison of the results with those given by the same samples at the Bradford Conditioning House showed very good agreement, the maximum discrepancy being about $\frac{1}{4}\%$ of the dry weight. This point seemed to us to require careful investigation, because certain experiments indicate that the process of drying proceeds for a very lengthy period (much longer than the time occupied by an ordinary regain test), so that the commercial "dry weight" is to a slight extent arbitrary and dependent on the exact drying routine.

III.—EXPERIMENTAL RESULTS

The general scheme of a series of experiments carried out after the control arrangements had been made satisfactory is outlined in Table I. The weight of the control cloth was first adjusted so as to give a medium humidity. After a week's run the control weight was diminished so as to give a smaller humidity, and after another week diminished again. The third run was near the limits of efficient working of the control. Further lightening of the control weight tended to produce a state of affairs in which the air was circulated continuously through the drying tower. The fourth and subsequent runs form a series of increasing humidity up to near the maximum possible. As the control weight is increased, a state of affairs is reached in which the air circulates continuously through the humidifying tower.

Table I.

Period	Control Weight (grm.)	Relative Humidity (%)
Sept. 9th to 16th	427	62·3
Sept. 16th to 23rd	422	55·4
Sept. 23rd to Oct. 1st ...	414	43·3
Oct. 1st to 26th	432	74·6
Oct. 26th to Nov. 7th ...	437	81·5
Nov. 7th to 14th	444	86·2
Nov. 14th to 23rd	450	90·0

Table II. gives the results of observation on a number of samples of different kinds of wool (including mohair). This table has been compiled from a much bulkier table giving the results of daily observations. The figures given in the body of the table are the percentage regains, *i.e.* the weight of moisture absorbed by 100 parts by weight of the dry material. The columns of the table have been arranged in order of magnitude of the relative humidity—the actual chronological order being given in Table I. The question of chronological order may prove to be of importance in connection with the possible existence of a hysteresis effect in the moisture absorption. We have found in the course of some work on the effect of finishing processes on the hygroscopic capacity, that very considerable hysteresis effects are exhibited in cycles of treatment involving such extreme processes as soaking in cold water or heating to a high temperature in a damp state, but that for such moderate changes as are involved in the present paper the hysteresis effects, if any, are quite small.

The last two lines contain values of the regain calculated from the data of Schloesing[2] and Hartshorne.[3]

Table II.

% Regain of Wool in Different Forms at Various Atmospheric Humidities

Relative Atmospheric Humidity %→		43·3	55·4	62·3	74·6	81·5	86·2	90·0
		regain	regain	regain	regain	regain	regain	regain
80's Botany	Raw wool ...	11·35	13·72	15·47	18·02	20·36	23·60	26·70
	Scoured wool ...	12·13	14·30	15·58	16·45	17·86	19·58	21·20
	Card ball ...	12·20	14·36	15·50	16·94	18·60	20·70	22·55
	Backwash ball	12·05	14·30	15·42	16·88	18·54	20·60	22·40
	Noil	11·90	13·66	14·92	15·75	17·10	18·80	20·30
	Top	11·85	14·06	15·10	16·68	18·28	20·40	22·25
56's Sydney Cross-bred	Raw wool ...	4·88	7·80	8·20	10·56	12·93	15·40	17·90
	Scoured wool ...	12·27	14·43	15·85	16·87	18·10	20·10	21·77
	Card ball ...	12·10	14·30	15·57	17·12	19·00	21·20	23·00
	Backwash ball	12·10	14·37	15·45	17·20	18·96	21·10	23·05
	Noil	11·74	13·80	15·18	16·10	17·60	19·40	21·18
	Top	11·90	14·10	15·36	16·84	18·30	20·40	22·14
	Yarn	12·25	14·36	15·36	16·90	18·70	20·55	22·20
Yks. Hog Wool about 40's	Raw wool ...	10·30	11·90	12·00	14·20	15·30	16·85	18·30
	Scoured wool ...	12·00	14·10	15·50	16·60	18·00	19·70	21·30
	Comb sliver ...	11·60	13·90	14·90	16·50	18·50	20·75	22·80
	Noil	10·95	12·75	14·07	15·27	16·66	18·47	20·20
	Top	11·63	13·75	14·88	16·35	17·93	20·10	21·90
Cape Wool about 64's	Raw wool ...	7·60	9·25	10·87	13·00	15·10	17·30	19·45
	Scoured wool ...	12·24	14·37	15·62	16·50	17·80	19·40	20·80
	Card sliver ...	12·10	14·40	15·49	17·00	18·60	20·70	22·40
	Backwash sliver	11·60	13·90	15·00	16·50	18·05	20·05	21·70
	Noil	11·93	13·95	15·41	16·06	17·40	19·00	20·15
	Top	11·35	13·50	14·57	16·18	17·70	19·60	21·30
Mohair (medium quality Cape)	Raw fleece ...	11·44	13·30	14·45	15·68	16·80	18·45	19·90
	Scoured ...	11·77	13·90	15·00	16·32	17·53	19·25	20·80
	Sliver 1st comb	12·40	14·58	15·73	17·03	18·90	20·80	22·72
	,, 2nd ,,	11·90	14·13	15·24	16·67	18·50	20·50	22·30
	Noil 1st ,,	11·77	13·78	15·00	16·13	17·40	19·13	20·70
	,, 2nd ,,	11·80	13·82	15·05	16·10	17·47	19·15	20·80
	Top	12·14	14·30	15·45	16·78	18·38	20·25	22·00
	Yarn	12·20	14·35	15·35	16·82	18·30	20·08	21·75
	Schloesing ...	12·5	14·2	15·0	17·5	19·1	21·5	24·0
	Hartshorne ...	11·6	14·0	15·5	18·5	20·4	22·1	23·6

The results for a series of finished cloths are shown in Table III. The values for dry spun worsted yarns calculated from the data of Schloesing and Hartshorne have been added for purposes of comparison.

Table III.

Relative Humidity of Atmosphere %→	43·3	55·4	62·3	74·6	81·5	86·2	90·0
	regain	regain	regain	regain	regain	regain	regain
Milled overcoating 22 oz., 64's quality, wool dyed	13·80	16·00	17·50	18·57	20·00	21·85	23·50
Cheviot suiting 16-17 oz., 50-56's quality, wool dyed	13·38	15·70	17·20	18·50	20·10	22·32	24·20
Saxony suiting 16 oz., 64-70's quality, wool dyed	13·10	15·40	16·70	18·00	19·40	21·50	23·20
2/2 Twill blue serge 16-17 oz., 64's quality, piece dyed	12·20	14·30	15·50	16·80	18·10	19·90	21·30
Coating serge 16 oz., 70's quality, piece dyed	—	—	—	16·17	17·49	19·06	20·16
Mean	13·12	15·62	16·72	18·01	19·02	20·93	22·47
Schloesing	12·50	14·20	15·00	17·50	19·40	21·50	24·00
Hartshorne	11·60	14·00	15·50	18·50	20 40	22·10	23·60

IV.—DISCUSSION OF THE RESULTS

The results shown in Table II. have been plotted in Figures 2–6. Each figure relates to one kind of material and the different forms are indicated by different kinds of marks. In each figure the curve has been drawn to represent values for the top.

It will be seen that there are differences between the different forms of the same material, which though small are unmistakable and show a certain degree of regularity.

The regains of the noils are in general smaller than those of the corresponding tops. This is to be expected since the noils contain a considerable

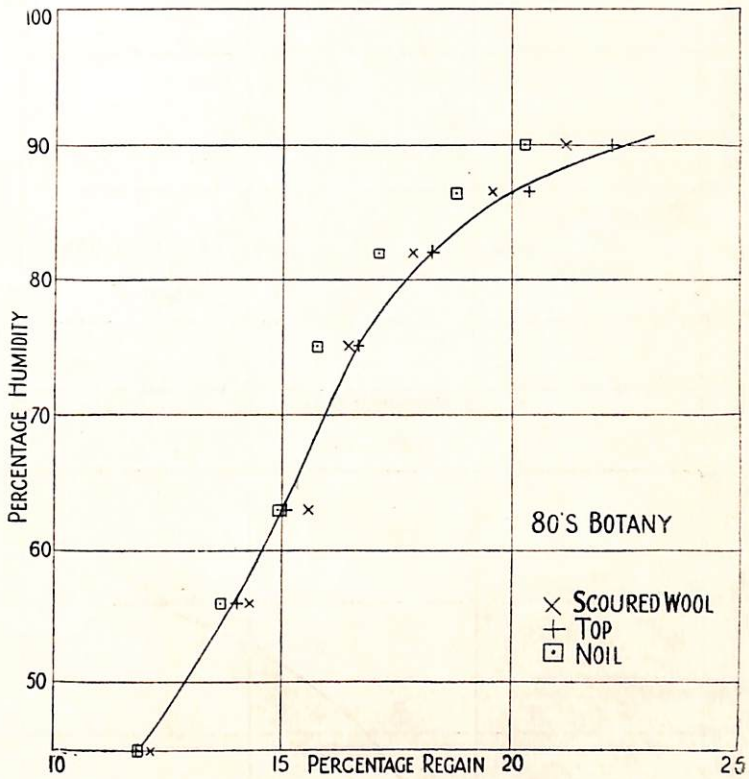

FIG. 2

amount of foreign matter of relatively small hygroscopic capacity. Moreover it is easy to see that if curves were drawn for the noils they would be of a rather different shape from the curves for the tops. The difference between the regain of the top and that of the noil is much greater at high than at low humidities. In the Cape wool the regain of the noil is actually greater than that of the top at the low humidities and less at high humidities.

The hygroscopic capacity of the scoured wool does not differ much from that of the top. The curves for the scoured wools would, however, run roughly parallel with those for the noils, showing the same tendency to give, relative to the top curves, high values at the lower humidities. Thus the mean values for the five kinds of material at the highest humidity are 21·17% for the scoured wools and 21·92% for the tops, showing a difference of 0·75 in favour of the tops, while the mean values at the lowest humidity are 12·08% and 11·77%, showing a difference of 0·31 in favour of the scoured wools. A comparison of the same kind between the scoured wools and

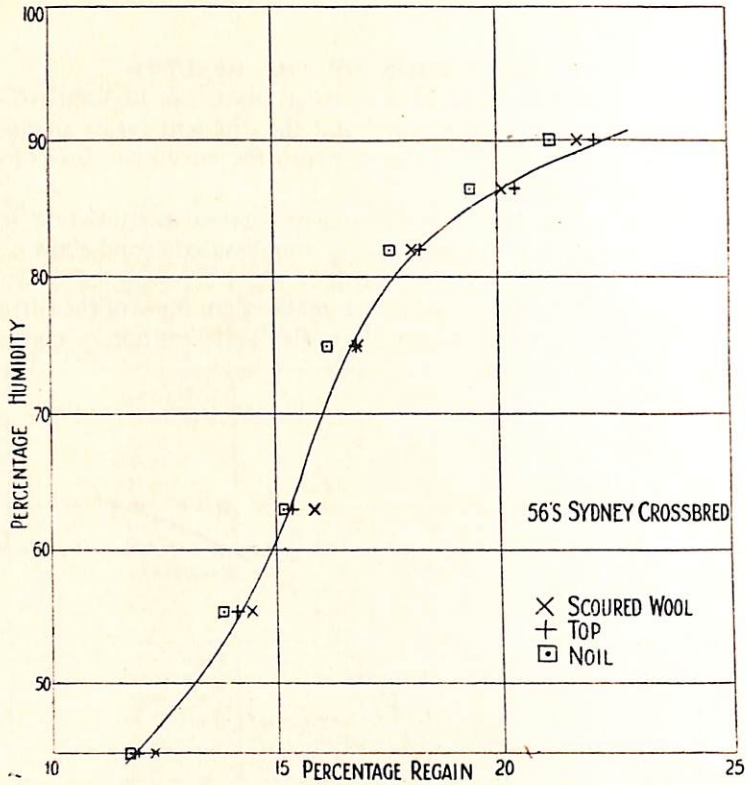
100
90
80
70
60
50
PERCENTAGE HUMIDITY
10
15
20
25
PERCENTAGE REGAIN
56'S SYDNEY CROSSBRED
SCOURED WOOL
TOP
NOIL

FIG. 3

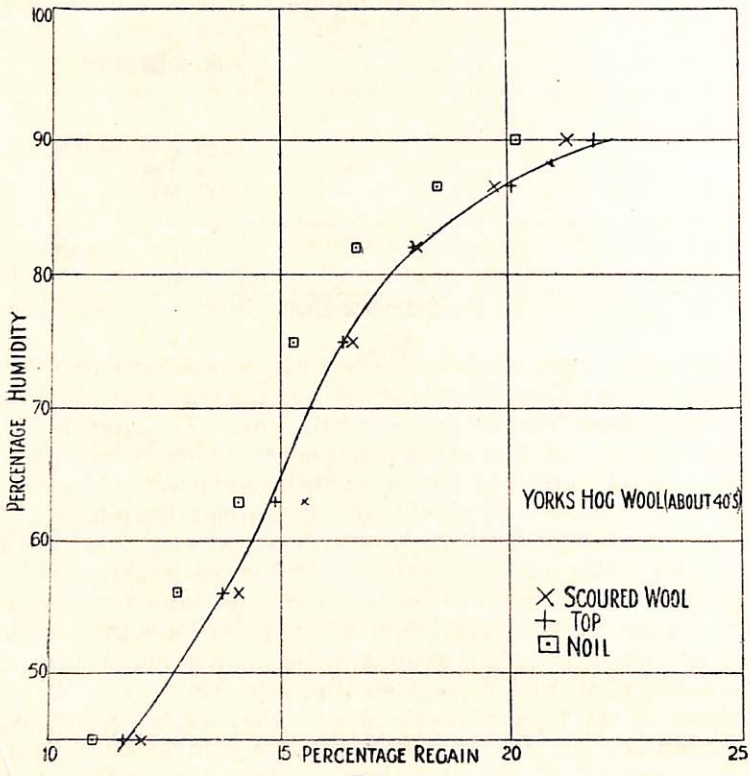
100
90
80
70
60
50
PERCENTAGE HUMIDITY
10
15
20
25
PERCENTAGE REGAIN
YORKS HOG WOOL(ABOUT 40'S)
SCOURED WOOL
TOP
NOIL

FIG. 4

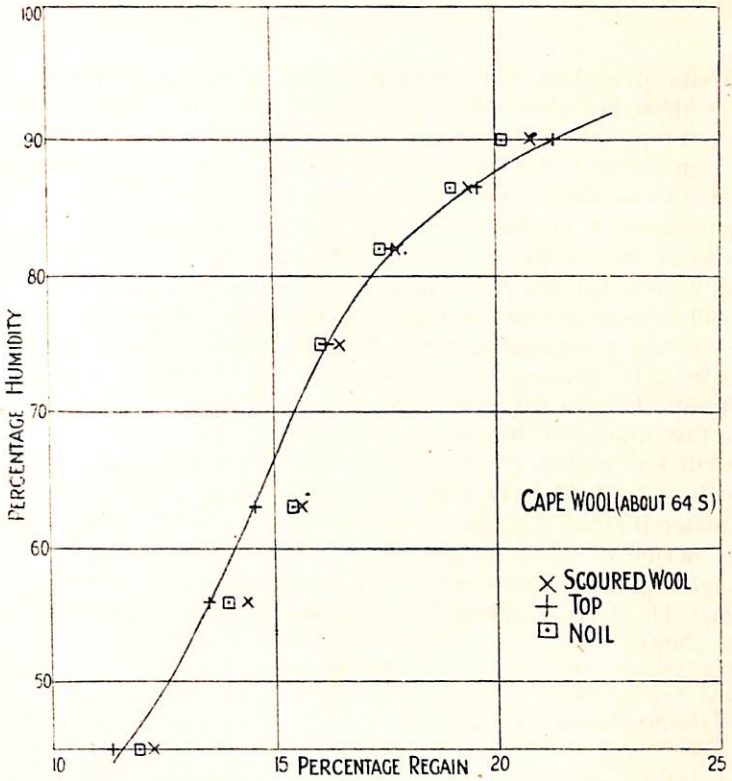
100
90
80
70
60
50
PERCENTAGE HUMIDITY
10
15
20
25
PERCENTAGE REGAIN
CAPE WOOL (ABOUT 64 S)
SCOURED WOOL
TOP
NOIL

FIG. 5

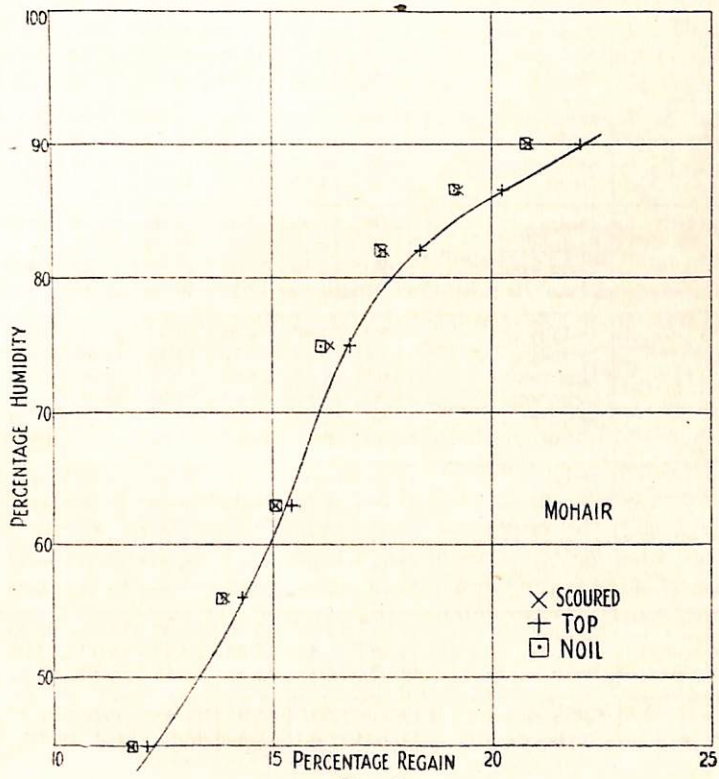
100
90
80
70
60
50
PERCENTAGE HUMIDITY
10
15
20
25
PERCENTAGE REGAIN
MOHAIR
SCOURED
TOP
NOIL

FIG. 6

noils would give differences—both in favour of the scoured wool—of 0·65 at the highest humidity and 0·42 at the lowest. We might at first sight expect the tops, which contain no vegetable matter, to show a higher regain than scoured wool. But the tops have had oil added which, as we shall see later, diminishes the hygroscopic capacity.

The reason for the difference in shape of the scoured wool and noil curves on the one hand, and the top curves on the other, is not so evident. The difference is possibly due to the presence of foreign matter in the scoured wool and noils.

It will be noticed that the regains of the yarns are practically the same as those of the corresponding top. This, of course, is to be expected, since in drawing and spinning the material has not undergone any treatment likely to affect its hygroscopic capacity.

The raw wools will be considered in Section VIII.

We will now consider the effect of the nature of the material. In Table IV. the figures in Table II. have, with some omissions, been rearranged, the form of the material being the basis of the main divisions of the rows of the table and the nature of the material being the basis of the sub-divisions. The figures relating to the different materials in the same form are thus brought together. The average values for the different materials in the same form are also shown.

Table IV.

Relative Humidity of Atmosphere %→		43·3	55·4	62·3	74·6	81·5	86·2	90·0
		regain	regain	regain	regain	regain	regain	regain
Scoured wool ...	80's Botany ...	12·13	14·30	15·58	16·45	17·86	19·58	21·20
	56's Sydney ...	12·27	14·43	15·85	16·87	18·10	20·10	21·77
	Yks. Hog wool...	12·00	14·10	15·50	16·60	18·00	19·70	21·30
	Cape wool ...	12·24	14·37	15·62	16·50	17·80	19·40	20·80
	Mohair	11·77	13·90	15·00	16·32	17·53	19·25	20·80
	Mean	12·08	14·22	15·51	16·55	17·86	19·61	21·17
Card ball... ...	Botany	12·20	14·36	15·50	16·94	18·60	20·70	22·55
	Sydney	12·10	14·30	15·57	17·12	19·00	21·02	23·00
	Cape wool ...	12·10	14·40	15·49	17·00	18·60	20·70	22·40
	Mean	12·13	14·35	15·52	17·02	18·73	20·86	22·65
Backwash ball ...	Botany	12·05	14·30	15·42	16·88	18·54	20·60	22·40
	Sydney	12·10	14·37	15·45	17·20	18·96	21·10	23·05
	Cape wool ...	11·60	13·90	15·00	16·50	18·05	20·05	21·70
	Mean	11·92	14·19	15·29	16·86	18·52	20·58	22·38
Noil	Botany	11·90	13·66	14·92	15·75	17·10	18·80	20·30
	Sydney	11·74	13·80	15·18	16·10	17·60	19·40	21·18
	Hog wool ...	10·95	12·75	14·07	15·27	16·66	18·47	20·20
	Cape wool ...	11·93	13·95	15·41	16·06	17·40	19·00	20·15
	Mohair	11·80	13·82	15·05	15·75	17·10	18·80	20·30
	Mean	11·66	13·59	14·93	15·79	17·17	18·89	20·43
Top	Botany	11·85	14·06	15·10	16·68	18·28	20·40	22·25
	Sydney	11·90	14·10	15·36	16·84	18·30	20·40	22·14
	Hog wool ...	11·63	13·75	14·88	16·35	17·93	20·10	21·90
	Cape wool ...	11·35	13·50	14·57	16·18	17·70	19·60	21·30
	Mohair	12·14	14·30	15·45	16·78	18·38	20·25	22·00
	Mean	11·77	13·94	15·07	16·56	18·12	20·15	21·92
Yarn	Sydney	12·25	14·36	15·36	16·90	18·70	20·55	22·20
	Mohair	12·20	14·35	15·35	16·82	18·30	20·08	21·75
	Mean	12·22	14·36	15·36	16·86	18·50	20·31	21·97
	Schloesing ...	12·5	14·2	15·0	17·5	19·4	21·5	24·0
	Hartshorne ...	11·6	14·0	15·5	18·5	20·4	22·1	23·6

It will be seen that the figures at any given humidity relating to different materials in the same form show very little variation. The figures for the Cape wool are undoubtedly lower than those for the other materials. Those for the Botany, Crossbred and Mohair are so close together that it is a difficult matter to arrange these materials in order of hygroscopic capacity. Regarding the figures for the top, the order would be—

Mohair—highest.
56's Crossbred—a very good second.
80's Botany.
Yorkshire Hog wool.
64's Cape wool—lowest.

There is evidently no relation between this order and the "quality" of the material. Moreover, such differences as are outside the range of experimental error are probably due to differences of treatment of the material, and it is conceivable that if the series of experiments were repeated with new samples, the materials would show a different order of hygroscopic capacity.

In this connection it would be interesting to investigate the coarser animal hairs (horse hair &c.). It is possible that they would give results not differing much from those given by wool.

In view of the fact that the material under investigation has been subject to processes likely to affect the hygroscopic capacity which have not been under our control (the object of these experiments was, of course, the investigation of ordinary commercial material), the results show a surprising agreement among themselves. Thus the highest value for the top at each humidity differs from the mean value by the respective amounts (beginning at the lowest humidity)—0·37, 0·36, 0·38, 0·28, 0·26, 0·25, 0·33. The lowest value (which at every humidity relates to the Cape wool) differs from the mean value by the amounts 0·42, 0·44, 0·50, 0·38, 0·42, 0·55, 0·62. The average value represents therefore the hygroscopic capacity of ordinary commercial tops in oil to a quite satisfactory degree of accuracy.

The figures given in Table III., relating to finished pieces, do not show anything like this degree of uniformity. Thus at the highest humidity the values of the regain vary from 24·20 to 20·16—a range of 4·04. In view of certain results which we have obtained as to the effect of finishing processes this extreme variability is not surprising. During dyeing and finishing the material may go through a number of processes of which some increase and some diminish the hygroscopic capacity. Some of these processes are of an extremely drastic nature, and the variability shown in Table III. is no more than is to be expected. Thus the process of hot-pressing may cause a reduction of as much as 3·5% in the regain at medium humidities[4] (*e.g.* 60%).

The agreement between our values and those given by Schloesing and Hartshorne is as good as can be expected in the absence of any information as to the treatment of the samples of these investigators. The most pronounced difference between our results and theirs seems to lie in the shape of the regain-humidity curves. Our curves are more markedly sigmoid (or S shaped) than those of Schloesing and still more so than those of Hartshorne.*

*It may be pointed out that a very small hysteresis effect would have a marked effect on the sigmoid nature of the curves, since on the low side of the point of inflexion we have been successively diminishing the humidity, while on the high side we have been successively increasing it. (See Table I.)

V.—THE EFFECT OF OIL ON THE HYGROSCOPIC CAPACITY

The main object of the present paper has been to measure the hygroscopic capacity of material which has been through ordinary commercial processes. It seems desirable, however, to consider a systematic investigation of one point, viz., the effect of oil on the hygroscopic capacity. To investigate this point a quantity of hosiery web was knitted from dry spun yarn (1/24's from 60's quality) and three samples were taken, of which the first was kept unaltered, and the second and third oiled with definite weights of olive oil. The oil was warmed slightly and distributed over the material in the form of small drops. The samples were then rolled up tightly and kept in a moderately warm room to allow the oil to distribute itself evenly. Such a method of oiling corresponds in a rough way with that adopted for oiling tops, and seemed to us therefore preferable to attaining a more even initial distribution by the use of a volatile solvent. The three samples then went through the usual routine of humidity variations and were dried out entire at the end. The percentages of oil reckoned on the weight of dry wool were 3·2 for the second sample and 10·6 for the third.

It was found that the effect of the oil is to diminish the hygroscopic capacity. The most obvious explanation of this effect is that the oil acts as non-hygroscopic matter which is reckoned in the dry weight, and so diminishes the calculated regain. If this explanation is correct, the ratio of the equilibrium regain of the unoiled sample to that of an oiled sample, should be equal to the ratio of the total weight of dry wool and oil in the oiled sample to that of the dry wool alone. This latter ratio is evidently equal to 1·032 in the case of the second sample, and 1·106 in the case of the third sample. In Table V. are given the values of the regains of the three samples and also the values of the ratio of the regain of the first (unoiled) sample to that of the second and third (oiled) samples.

Table V.

REGAINS OF UNOILED AND OILED SAMPLES

% Humidity	Regain of Unoiled Sample (R_1)	Regain of Sample with 3·2% of Oil (R_2)	Regain of Sample with 10·6% of Oil (R_3)	Ratio R_1/R_2 (compare with 1·032)	Ratio R_1/R_3 (compare with 1·106)
43·3	12·45	11·80	11·10	1·055	1·123
55·4	14·30	13·40	12·68	1·067	1·128
62·3	15·40	14·27	13·56	1·079	1·136
74·6	17·20	16·44	15·54	1·046	1·107
81·5	18·66	17·90	16·94	1·042	1·102
86·2	21·05	20·36	19·18	1·039	1·098
90·0	22·74	22·70	20·70	1·018	1·099

The average values of the ratios in the last two columns are 1·042 and 1·113 respectively, which are in fairly good agreement with the theoretical values. Both ratios are slightly larger than theory indicates, but the differences lie within the limits of experimental error. We may say therefore that the effect of oil is mainly that of a mere loading of the wool with non-hygroscopic material, and that there is possibly a very slight further effect in *diminishing* the actual absorptive power of the wool.

This conclusion regarding the effect of oil is verified in a roughly quantitative way by other data relating to cloth in the grey and after-scouring,

and to yarn before and after scouring. In the following table are given the values of the ratio of regain scoured to regain in the grease for samples of two woollen pieces and a woollen yarn.

Table VI.

% Atmospheric Humidity	Values of Ratio of Regain Scoured to Regain in Grease		
	Medium Woollen 15 oz., 48-50's quality	Medium Woollen 12 oz., 60's quality	Cheviot Yarn
43·3	1·07	1·10	1·09
55·4	1·10	1·11	1·10
62·3	1·14	1·10	1·10
74·6	1·10	1·12	1·10
81·5	1·09	1·12	1·08
86·2	1·08	1·10	1·08
90·0	1·06	1·09	1·08

The theoretical values of the oil content corresponding to the mean values of the ratios are 9%, 11% and 9% respectively. These values are rather low. The usual percentage of oil for these materials would be from 10 to 12 on the conditioned weight. The discrepancy is explicable on the ground that the hygroscopic capacity of the materials has been slightly impaired in the drying. It would not require a very large effect of this kind to produce a considerable decrease in the theoretical value of the oil content.

This result has a bearing on the question of the regain of tops or yarn in oil compared with that of dry tops or yarns. We have not been able to obtain a comparison of the same material drawn and spun by the two different methods. We have, however, data for dry spun yarn which we can compare with the mean results for tops in oil. As will be seen from the preceding sections, tops and yarn of the same kind are practically identical in regain. The result of the comparison is shown in Table VII. Two samples of yarn were investigated.

Table VII.

% Humidity	Percentage Regain of			Values of	
	Tops in Oil (R_1)	Dry Spun Yarn 1/24's, 60's quality, Sample A (R_2)	Dry Spun Yarn 1/24's, 60's quality, Sample B (R_3)	Ratio R_1/R_2	Ratio R_1/R_3
43·3	11·77	12·30	12·05	1·045	1·024
55·4	13·94	14·40	13·68	1·033	1·019
62·3	15·07	15·60	14·57	1·035	1·033
74·6	16·56	17·34	16·78	1·047	1·013
81·5	18·12	18·50	18·48	1·021	1·020
86·2	20·15	20·28	21·02	1·006	1·043
90·0	21·92	22·13	23·84	1·010	1·087
		Averages		1·028	1·034
		Average of both series ...		1·031	

This ratio (1·03) is what we should expect in the case of dry tops (or yarn) and ordinary tops (or yarn) in oil, since the latter contains in general rather less than 3% of oil.* This difference of 3% corresponds to a difference in favour of dry tops of 0·6% regain in the neighbourhood of 19% regain. The actual difference in the standards for tops in oil and dry tops is 0·75 in the opposite direction.

VI.—THE ATMOSPHERIC HUMIDITY CORRESPONDING TO THE DIFFERENT STANDARDS OF REGAIN

One indispensable preliminary to any investigation of the question of standards of regain is the determination of the atmospheric humidity corresponding to the present standards.

To obtain such values of the humidity, curves were constructed from the mean values given in Tables III. and IV. and the humidity corresponding to the appropriate standard regain deduced from each curve. For yarns in oil the mean curve for the tops in oil was used, since it related to five different materials, while only two different yarns were actually investigated. For dry tops and yarns a curve was constructed from the mean values for the tops in oil, increased in the ratio 1:1·03. This curve was found to be in excellent agreement with the available data relating to dry spun yarn.

The values of the humidity corresponding to the different standards are given in Table VIII. With the exception of the figures for cloth, the figures may be said to represent fairly accurately the behaviour of the ordinary material of commerce. The extreme variability of finished cloth makes the figure for cloth subject to considerable uncertainty.

Table VIII.

Material	Standard Regain (%)	Relative Humidity (%) necessary to give the Standard Regain
Noils	14	58
Scoured wool	16	70
Cloth	16	55—72
Yarn (dry)	18¼	80·5
Yarn (in oil)	18¼	83
Tops (dry)	18¼	80·5
Tops (in oil)	19	85

The above values correspond to equilibrium at 72° F. At present it is not possible to work with the Humidity Room at a much lower temperature. The effect of changes of temperature at constant relative humidity is, however, small, though by no means negligible. The effect of temperature has been studied by Schloesing and his results, which pass very satisfactorily a certain thermodynamical test (as is shown in another communication), will be used here to extend the above table to lower temperatures.

The results of the calculations from Schloesing's figures are given in Table IX. The general method of the calculations is shown in Appendix C.

* Strictly speaking, the theoretical figure equals the percentage reckoned on the dry weight and corresponds to a rather smaller percentage on the conditioned weight.

Table IX.

Material	Standard Regain (%)	Relative Humidity required to give Standard Regain at			
		72°F	70°F	60°F	50°F
Noils	14	58	58	55	52
Scoured wool	16	70	70	67	65
Cloth	16	63*	63*	60*	58*
Yarn (dry)	18¼	80·5	80	78	76
Yarn (in oil)	18¼	83	83	81	79
Tops (dry)	18¼	80·5	80	78	76
Tops (in oil)	19	85	85	83	81

* These, of course, are mean values. For a cloth of high hygroscopic capacity, such as the Cheviot suiting in Table III., they would be much lower; for a cloth of low capacity, such as the coating serge in Table III., they would be much higher.

VII.—REGAIN AND HUMIDITY IN ORDINARY ATMOSPHERES

To obtain some idea of the natural variation of humidity and regain, two series of experiments were carried out. In one series a sample of scoured white worsted cloth was kept in the laboratory and weighed twice a day, at about 9.15 a.m. and 4.45 p.m. The sample was kept in a muslin cage which protected it from dust and at the same time allowed free access of the air of the room. At the time of weighing the temperature and humidity were observed—the latter by means of the Assmann hygrometer. A similar series of measurements were made with a number of samples kept in a box fixed externally on an outside wall. The bottom and sides of the box contained large apertures covered with perforated zinc (outside) and muslin (inside), so as to allow free access of air with the minimum of dust.

The samples included pieces of—

(1) Scoured white worsted cloth.
(2) Finished hosiery web.
(3) Botany top (80's).
(4) Crossbred top (Sydney 56's).

All four were tested in the outside box; only (1) inside.

The results of the daily observations are too numerous to reproduce. In Tables X. and XI. are given therefore the monthly averages and also the average for the whole year.

Table X.

Month	Mean Temperature (°F)	Mean Humidity (%)	Regain of Samples in Outside Box			
			Worsted Cloth (%)	Web (%)	80's Botany (%)	56's Sydney (%)
February 1923	44·15	84·35	24·58	20·04	22·71	21·14
March	46·90	73·50	20·20	18·02	19·31	19·39
June	61·60	77·10	14·76	14·09	15·07	15·07
July	68·70	76·80	15·99	14·83	16·33	16·08
August	62·30	82·30	18·03	16·19	17·77	17·44
September ...	58·20	80·80	17·60	16·10	17·37	17·23
October ...	51·64	81·44	19·72	17·45	19·41	19·31
November ...	39·85	83·00	22·19	19·21	21·38	21·98
December ...	38·95	88·50	25·32	21·21	23·96	24·63
Average for Year	52·48	80·87	19·82	17·46	19·15	19·14

Table XI

Month	Mean Temperature (°F)	Mean Humidity (%)	Regain of Sample in Laboratory. Worsted Cloth (%)
March 1923	58·70	50·70	14·67
June	60·10	77·40	16·23
July	66·40	78·90	16·96
August	62·25	79·40	17·41
September	60·72	77·70	16·56
October	58·80	69·44	16·34
November	54·50	70·20	15·14
December...	55·60	66·20	15·05
Average for Year ...	59·63	71·24	16·04

Several interesting points are immediately evident from these figures. The outdoor samples have the highest regain in winter and the lowest in summer, whereas the indoor sample varies in just the opposite manner. The reason for this is very simple. In winter the natural humidity out of doors is generally greater and the temperature lower than in summer—both factors therefore favouring a high regain in winter. Indoors, however, the humidity depends largely upon the amount the air is raised in temperature above the outside air. In summer the temperature will be roughly the same inside and out, and may even be at times lower inside. The inside and outside humidities will therefore not differ much. In winter, however, the inside humidity will be very much less than that outside, owing to the large temperature difference. It will be seen from the figures that the relation between the indoor and outdoor humidities varies in the above manner.

It will be seen that the outdoor average for the two samples of top is very near to the official standard for tops in oil and that the indoor average for the sample of cloth is very near to the official standard for cloth.

In view of the great variability of finished pieces the question of the indoor average requires a rather more careful examination. We must try to find out whether the particular sample of cloth may be considered an average sample. The figures relating to the outdoor samples enable us to do this. Let us compare the mean value for the tops in Table X. with the value for the cloth—

Mean value for tops	19·1%
Value for cloth	19·8%
Difference	0·7%

Now let us compare the mean values for tops and for finished cloths given in Tables IV. and III. respectively. Taking the values which lie near to 19% we have—

Mean values for tops	...	18·12	...	20·15
Mean values for cloths	...	19·02	...	20·93
Differences ...	...	0·90	...	0·78
Mean difference ...	...	0·84		

We thus see that the sample of cloth may be considered as representative of the average of the pieces dealt with in Table III.

VIII.—RAW WOOLS

The consideration of the raw wools has been postponed to the end of the paper because they differ from all other forms of wool in the irregularity of their behaviour with regard to the absorption of moisture.

The results for the raw wools are shown in Tables XII. and XIII. Table XIII. gives the results of a series of observations carried out three months earlier than those tabulated in Table XII. (which were simultaneous with the observations on tops, noils &c. recorded in Section III.).

Table XII.

Material	Percentage Regain at Relative Humidities of						
	43·3%	55·4%	62·3%	74·6%	81·5%	86·2%	90·0%
Botany (80's) ...	11·35	13·72	15·47	18·02	20·36	23·60	26·70
Sydney (56's) ...	4·88	7·80	8·20	10·56	12·93	15·40	17·90
Yks. Hog wool (40's)	10·30	11·90	12·00	14·20	15·30	16·85	18·30
Cape wool (64's) ...	7·60	9·25	10·87	13·00	15·10	17·30	19·45
Mohair	11·44	13·30	14·45	15·68	16·80	18·45	19·90

Table XIII. (Earlier Series)

Material	Percentage Regain at Relative Humidities of				
	74%	79%	84%	89%	94%
Botany (80's)...	17·99	20·80	22·55	28·20	33·90
Sydney (56's)...	10·46	12·48	14·53	18·95	23·75
Yks. Hog wool (40's) ...	13·60	14·72	15·99	18·74	21·50
Cape wool (64's)	—	15·16	17·69	22·02	26·43
Mohair	14·90	16·45	17·96	20·68	23·34

Three points are immediately evident from the tables—

(1) The great difference between the samples.

(2) The exceptionally high hygroscopic capacity of the fine Botany wool, especially at high humidities.

(3) The loss of this high hygroscopic capacity with age.

This irregularity of behaviour and the indication of a time effect are not surprising when it is remembered—

(1) That wool grease plays an important part in the water absorption.

(2) That the amount of wool fat varies with different wools.

(3) That the amount of non-hygroscopic matter (dirt and sand) also varies.

(4) That the foreign matter in wool is subject to putrefaction and other changes.

In order to show the difference between the scoured and greasy wools and its dependence on the kind of wool, the results at the highest humidity are shown in Tables XIV. and XV. The differences between the regain of the greasy wool and that of the scoured wool are shown in the fourth column, together with a letter "S" or "G," according as the scoured wool or the greasy wool is the more hygroscopic.

Table VIX.

EARLIER SERIES. 93% HUMIDITY.

Material	Greasy	Scoured		Difference
Botany	33·90	24·28	G	9·62
Crossbred	23·75	25·20	S	1·55
Yks. Hog wool	21·50	24·71	S	3·21
Cape wool	26·40	23·90	G	2·50
Mohair	23·34	24·18	S	0·84

Table XV.

LATER SERIES. 90% HUMIDITY.

Material	Greasy	Scoured		Difference
Botany	26·70	21·20	G	5·50
Crossbred	17·90	21·77	S	3·87
Yks. Hog wool	18·30	21·30	S	3·00
Cape wool	19·45	20·80	S	1·35
Mohair	19·90	20·80	S	0·90

The relation between the regain of greasy wool and that of the same wool scoured will depend upon the relation between the hygroscopic capacities of the actual wool and of the foreign matter. The hygroscopic capacity of the foreign matter will depend upon the relative amounts of wool grease (which is very hygroscopic) and sand or dirt.

The results shown in Table XIV. would seem to indicate that the high regains of the Botany and Cape wool are due to the large amount of grease they contain, and that the latter wool is less hygroscopic than the former owing to the larger amount of dirt it contains.

This point and the question of the decrease of the hygroscopic capacity with age are evidently matters for more detailed investigation.

APPENDIX A

As an example of the degree of concordance between the absolute and dew-point methods, the following portion of the humidity record may be given—

Date	Relative Humidity (%)		Mean Value from	
	Absolute (Single)	Dew Point	Absolute and Dew Point	All Methods
September 14th ...	62·1	61·8	62·1	62·3
,, 15th ...	—	61·8		
,, 16th ...	62·5	62·1		
September 19th ...	—	54·5	55·2	55·4
,, 20th ...	55·7	—		
,, 21st ...	—	54·8		
,, 23rd ...	56·2	55·0		
September 24th ...	—	43·5	43·7	43·3
,, 25th ...	43·2	—		
,, 26th ...	44·7	—		
,, 29th ...	—	43·5		

APPENDIX B

We will briefly consider the question of the accuracy of the results. The weighings were accurate to one part in about 5,000, so that no perceptible error can arise in this respect. The main source of error arises from the fluctuations of humidity in the room. Another source of error is probably the variation of the different samples of what is nominally the same material. As proved in another communication the hygroscopic capacity of wool is very sensitive to thermal treatment, so that we may expect variations in the same lot. Considering all the facts, we may say that any given value may be subject to an error of 0·1% regain in either direction.

It may be pointed out that though the humidity fluctuates about a mean value (see Fig. 1), the regains of the samples do not fluctuate in a corresponding manner. The samples tend so slowly to equilibrium with the atmosphere that the short period fluctuations of the atmospheric humidity will produce very little effect on the samples.

A similar smoothing-out of small-period fluctuations occurs with the glycerine hygrometer. When the room has reached a steady state the glycerine solution attains a composition corresponding to the average humidity.

APPENDIX C

As the temperature rises, the regain corresponding to a given relative humidity decreases slightly, and conversely the humidity corresponding to a given regain increases slightly. This is in accordance with thermodynamical principles. A body which, like wool, absorbs water with evolution of heat, should exhibit this relationship.[4]

The values for the necessary increase of percentage humidity per degree F. rise of temperature to maintain a constant regain are given in the following table. They have been calculated from a smooth curve drawn to fit values deduced from Schloesing's figures.

Regain (%)	Increase of % Humidity per °F.
14	·225
16	·212
18¼	·193
19	·185

By means of these values the humidities corresponding to the various regains have been calculated for temperatures below 72° F.

REFERENCES

[1] A hygrometer depending for its action on the changes of weight of a sample of wool was patented by Hartshorne in 1900 (U.S.A. Patent 648,868).

[2] Schloesing, Bull. Soc. Encour. Indust. Nat., 1893. The slightly condensed version by Mr. Samuel S. Dale, published in the Textile World Record (Nov. 1908), is not merely a perfectly adequate translation, but from the point of view of the exposition of the ultimate results of the work is rather more convenient than the original. This translation is issued as a pamphlet by the Manchester Testing House.

[3] Transactions of the National Association of Cotton Manufacturers, No. 79, p. 194, 1905; No. 90, p. 281, 1911.

[4] Private publication of the British Research Association for the Woollen and Worsted Industries, No. 33.

REGAIN

Explanatory Note.

Relative Humidity—This is a numerical measure of the dryness or dampness of the air. If the air is saturated and will absorb no more moisture, we say the relative humidity is 100%. If the air is absolutely devoid of moisture, we say the relative humidity is 0%. In this climate the natural relative humidity of the atmosphere may be very low (as on a bright frosty morning) or it may be nearly 100% (as in misty weather).

The degree of dryness or dampness of the atmosphere depends not merely on the amount of moisture in a given volume of air, but on the relation between this amount and the amount required to saturate the air. This latter amount varies very rapidly with the temperature. Thus at 40° F. it is 2·9 grains per cubic ft.; at 50°, 4·1; at 60°, 5·8; at 70°, 8·0; and at 80°, 11·0. Roughly speaking, a rise of temperature of 20° F. doubles the amount of moisture required to saturate the air.

It follows therefore that if we are merely told the amount of moisture in the air, say 4 grains per cubic ft., we have no information as to the dryness or dampness of the air. If the temperature were 50° F. the air would be nearly saturated; if 70° F. the air would be fairly dry, containing only half the amount of moisture required to saturate it; at a still higher temperature the air would be still drier.

The state of the atmosphere with respect to dryness and dampness is thus specified by the actual moisture content expressed as a fraction or a percentage of the amount required to saturate the air. Thus 4 grains per cubic ft. corresponds to 98% relative humidity at 50° F. and to 50% at 70° F. In the following table are given as an illustration of this the grains per cubic ft. corresponding to different percentage humidities at different temperatures.

Temp. °F.	Relative Humidity (percentage)									
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
40	2·86	2·57	2·09	2·00	1·72	1·43	1·14	0·86	0·57	0·29
50	4·10	3·69	3·28	2·87	2·46	2·05	1·64	1·23	0·82	0·41
60	5·77	5·19	4·62	4·04	3·46	2·89	2·31	1·73	1·15	0·58
70	8·01	7·21	6·41	5·61	4·81	4·01	3·20	2·40	1·60	0·80
80	10·98	9·88	8·78	7·69	6·59	5·49	4·39	3·29	2·20	1·10
90	14·85	13·37	11·88	10·49	8·91	7·43	5·94	4·46	2·97	1·49
100	19·84	17·86	15·87	13·89	11·90	9·92	7·94	5·95	3·97	1·98

Regain—It is common knowledge that various substances, such as wool, cotton, linen, paper, leather, tobacco, wood &c. absorb moisture to a degree depending upon the atmospheric conditions. This power of absorbing moisture seems to be due to the extremely fine sponge-like structure possessed by these bodies. Such substances are called colloids. They possess properties very different in many respects from the so-called crystalloids or bodies with a crystalline structure, *e.g.* soda crystals.

Now the precise estimation of the amount of water in such materials as wool (which is expensive and absorbs large quantities of moisture) is of great importance commercially. This amount is specified by means of a quantity called the "regain." The regain of a sample of wool is the amount of water it contains expressed as a percentage of the dry weight (not as a percentage of the total original weight). Thus if a 1 lb. sample lost 3 oz. on drying, the regain would be 3 oz. expressed as a percentage not of 1 lb. but of 13 oz., *i.e.* it would be—

$$\frac{3 \times 100}{13} \text{ or } 23{\cdot}08\% \text{ Regain.}$$

The dry weight of 13 oz. would have to regain 23·08% to get back to its original weight of 1 lb., hence the term "regain."

Standard Regain—For convenience and avoidance of disputes, certain standards of regain are recognised, *e.g.* 18¼% for yarn. Yarn at this regain is regarded as correct, and if it has more or less moisture an allowance is deducted from or added to the price. It is by no means certain that the Standard Regains in this country are the most suitable for the climate and for safe storage. Other countries impose other standards. This question is under investigation by the Association.

Dry Weight—The "dry weight" of a sample of wool is defined as the weight obtained by drying the sample in an oven in a current of air at a temperature of from 220° to 230° F. till no perceptible change of weight is detectable in consecutive weighings at an interval of about 8 minutes.

Equilibrium Regain—When wool in any form (top, cloth &c.) is placed in an atmosphere of constant temperature and humidity, it will in general begin to gain or to lose moisture. This process will go on for some time, but at a gradually diminishing rate, till finally the wool attains a certain weight and regain. This regain is called the "equilibrium regain." The determination of this equilibrium regain for different humidities and temperatures is a matter of considerable importance.

This information, however, is necessary for the proper understanding and control of certain industrial processes. For example, in French drawing, artificial humidification is necessary for the satisfactory processing of the wool, since the regains corresponding to ordinary indoor conditions are too low. Again, such knowledge of the relation between regain and atmospheric conditions affords information as to the capabilities of a conditioning room for yarn or hosiery. The regain of wool exposed to ordinary atmospheres in this country varies over a wide range—roughly from 30% to 12%. The upper limit would correspond to a nearly saturated atmosphere—the lower to a relative humidity of about 45% (which for our climate is very low).

Hygroscopic Capacity—The power of absorbing moisture.

Hysteresis—This is the dependence of the state of a body not merely on the external influences operating at the time, but also in the way these influences have been operating previously. A familiar example occurs in magnetism. Thus the magnetism produced in a bar of iron does not depend merely upon the actual magnetising force operating at the instant, but also on how the magnetising force has been operating previously. If, for example, the magnetising force be increased from zero in steps up to a certain value and then decreased in the same steps, the magnetism produced at any stage will not be the same when the magnetising force is decreasing as it is when it is increasing. When the external magnetising force becomes zero, the bar may be strongly magnetised. This is magnetic hysteresis. On the other hand, a perfectly elastic spring does not show hysteresis. A certain load always corresponds to a definite sag or extension. It does not matter whether the load is increasing or decreasing.

THE THERMODYNAMICS OF WATER ABSORPTION BY TEXTILE MATERIALS

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Thermodynamical reasoning seems first to have been applied to the phenomenon of water absorption by textile materials in a paper by Trouton[1] who showed that if the latent heat of evaporation of water from the material is equal to the latent heat of evaporation of water in bulk, then the moisture content of the material depends only on the relative humidity of the atmosphere with which it is in equilibrium.

Though Trouton's conclusion follows quite logically from his premiss, neither premiss nor conclusion is true of textile materials. Now the absorption of water in the liquid form by textile materials is accompanied with considerable evolution of heat, so that the latent heat of evaporation of water from the material must be greater than the ordinary latent heat of evaporation, and Trouton's premiss is not true. On the other hand, Schloesing[2] has shown that the regain of textile materials in equilibrium depends not merely on the relative humidity, but also on the temperature.

By means of thermodynamical reasoning of a more general nature than that of Trouton it is possible to deduce a quantitative relation between the heat of water absorption and data relating to regain, humidity and temperature. This relation is in fact a form of the Kirchhoff equation[3] connecting the heat of dilution of a solution with vapour pressure data. In the case of an aqueous solution of a non-volatile solute, Kirchhoff's formula may be written—

$$Q = \rho T^2 \frac{d}{dT} log \frac{p}{P} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where Q is the heat of dilution of the solution (*i.e.* the heat evolved when unit mass of water is added to a large volume of solution), ρ the gas constant for unit mass of water vapour, T the absolute temperature, p and P the vapour pressures of the solution and pure water respectively. The concentration of the solution is, of course, supposed to remain constant during the differentiation.

To adapt this equation to the case of a textile material we must write $H=p/P$ where H is the relative humidity of the atmosphere. The equation then becomes—

$$Q = \rho T^2 \left(\frac{d \, log \, H}{dT} \right)_R \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where Q now is the heat of water absorption, *i.e.* the heat evolved when unit mass of water is absorbed evenly into a large mass of the material, and R is the regain. This equation connects the heat of water absorption with the way in which the humidity has to vary with the temperature in

order to preserve a constant regain. Trouton's theorem is a special case of the equation in which both sides are equal to zero. With textile materials both sides are positive—heat is evolved when water is absorbed and the atmospheric humidity corresponding to a given regain increases with the temperature (or the regain corresponding to a given humidity decreases with rise of temperature).

With respect to this diminution of hygroscopic capacity with rise of temperature, Schloesing[2] remarks, "This slight influence of temperature is worthy of attention. It is not peculiar to textile materials; it has been observed in vegetable earth and tobacco; it may indicate a general property of hygroscopic substances." We see from the above thermodynamical relation that the effect is a general property of hygroscopic substances which absorb water with the evolution of heat.

We will now calculate the heat of absorption of water by cotton, silk and wool, from the data given by Schloesing.[2] These data are in a form very convenient for our purpose. Schloesing measures at three different temperatures the relative humidity of air in equilibrium with material containing a given percentage of moisture. The Kirchhoff formula may be written—

$$Q = -\frac{\rho d \log H}{d\,(1/T)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Now suppose that a certain regain is maintained by a humidity H_1 at an absolute temperature T_1, and by a humidity H_2 at a temperature T_2. Substituting finite increments for the infinitesimal increments in the above formula, we obtain—

$$Q = \frac{\rho T_1 T_2 (\log H_2 - \log H_1)}{T_2 - T_1} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

a formula which is valid so long as the heat of absorption does not vary appreciably between the temperatures T_1 and T_2.

Let us consider an example of the application of this final formula to Schloesing's results. American cotton containing 5·1% regain is in equilibrium with an atmosphere of 35·0% humidity at 12° C., with one of 39·0% humidity at 24° C., and with one of 42·1% humidity at 35° C. Using the extreme values we have $T_1 = 285$, $T_2 = 308$, $H_1 = \cdot 350$, $H_2 = \cdot 421$, $\log H_2 - \log H_1 = 2\cdot 303 \times (\bar{1}\cdot 6243 - \bar{1}\cdot 5441)$. We have also $\rho = 1\cdot 99/18$ calories per gram-degree. Hence we have—

$$Q = \frac{1\cdot 99 \times 285 \times 308 \times 2\cdot 303 \times \cdot 0803}{18 \times 23} \text{ cal. per grm.}$$

$$= 78 \text{ cal. per grm.}$$

It is very convenient for our purpose that all Schloesing's experiments were carried out at the same set of temperatures. Hence if we use, as in the above calculation, the extreme temperatures, we may write—

$$Q = \frac{1\cdot 99 \times 285 \times 308 \times 2\cdot 303 \times (\log_{10} H_2 - \log_{10} H_1)}{18 \times 23}$$

or

$$Q = 970 \times (\log_{10} H_2 - \log_{10} H_1)$$

In Table I. are given Schloesing's data and the values of the heat of absorption calculated by means of the above formula.

TABLE I.—The Heat of the Absorption of Water by Textile Materials

Material	Regain Parts water per 100 parts dry material	Percentage Humidity		$log_{10} H_2 - log_{10} H_1$	Q calories per grm. of water absorbed
		at 12° C. ($H_1 \times 100$)	at 35° C. ($H_2 \times 100$)		
American Cotton	5·1	35·0	42·1	·0802	78
	7·2	59·1	66·1	·0486	47
	10·3	77·6	83·4	·0313	30
	13·75	87·9	90·9	·0146	14
Egyptian Cotton	4·3	22·4	29·5	·1196	116
	8·15	62·4	67·8	·0360	35
	15·5	88·8	92·6	·0182	18
Indian Cotton ...	5·75	40·3	44·3	·0411	40
	8·6	60·4	66·6	·0425	41
	16·15	91·0	92·4	·0067	6
B.A. Crossbred Wool, combed	11·2	33·1	44·2	·1256	122
	15·25	61·6	70·6	·0592	58
	19·1	77·4	85·2	·0417	41
	27·6	93·2	96·3	·0142	14
Port Philip Merino Wool, combed	8·3	24·5	31·8	·1132	110
	14·9	57·5	69·4	·0817	79
	21·9	83·1	89·2	·0308	30
	29·0	95·4	96·1	·0032	3
Raw Cevennes Silk	7·5	31·6	38·3	·0835	81
	9·7	50·5	61·7	·0870	85
	14·2	75·0	81·9	·0382	37
	16·5	83·9	88·1	·0212	20
	25·6	94·8	95·1	·0014	1
Boiled-off Cevennes Silk	6·55	27·9	37·0	·1226	119
	11·6	65·3	76·8	·0705	69
	14·65	79·6	84·7	·0270	26
	22·0	94·3	95·6	·0060	6
Raw China Silk	7·4	34·1	38·2	·0493	48
	12·35	67·3	77·3	·0602	58
	17·1	86·8	89·5	·0133	13
	23·8	95·2	96·8	·0073	7
Boiled-off China Silk	6·1	31·1	36·0	·0635	62
	11·65	68·9	78·2	·0550	53
	14·95	83·6	86·6	·0153	15
	23·3	94·1	94·8	·0032	3

The values of the heat of water absorption are shown plotted in Fig. 1 and Fig. 2. In view of the fact that the calculated values depend upon small differences between pairs of values of the relative humidity, they may be considered to fit very well to smooth curves.* Moreover, these curves are of the type we should expect on theoretical grounds. When the fibre is dry the attraction for water molecules is very great, so that we get a large heat of absorption. As the water content increases the intensity of the attraction and consequently the heat of absorption diminish. As saturation approaches the water absorption approximates more and more to a mere coarse-grained soaking up of water, such as occurs with a sponge, so that the heat of absorption approaches zero.

* These curves are the full lines. The broken lines will be referred to later in the paper.

This change in the nature of the process of absorption as the moisture content increases is also shown by the shape of the regain-humidity curve[4] and by the mode of variation of the rate of evaporation.[5] Observations of the swelling of wool fibres in atmospheres of different humidities by H. R. Hirst[6] and of the specific gravity of wool at different regains by A. T. King[7] show that the absorption of water is accompanied by a diminution of total volume which is large at low regains and diminishes with increasing regain, approaching zero at saturation.

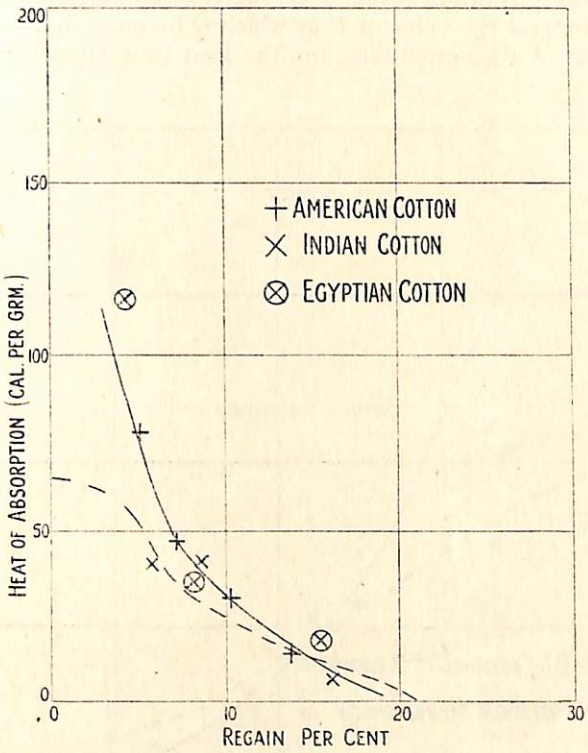

FIG. 1

It will be seen that the values of the heat of absorption become very high at low regains. The range of Schloesing's results is too limited for us to extrapolate our values to zero regain, but it is easy to see that at zero regain we get a value in the case of wool which is actually comparable with the latent heat of evaporation of water.*

The heat of absorption as defined above is not a quantity which can readily be measured experimentally. The most convenient magnitude for experimental measurement is the heat evolved when the material at any given regain is completely wetted. This "heat of wetting" or "heat of soaking" is very simply related to the heat of absorption. If a mass of

* Dry wool is perceptibly heated both when it picks up moisture from the air and when it is wetted. In the former case we have evolved both the heat of wetting and the ordinary heat of evaporation. The latter case is the more familiar in the industry. In the former case the slowness of absorption prevents excessive heating.

material whose dry weight is 100 grm. and regain is R has its regain increased to $R + \delta R$, the heat evolved is $Q \delta R$. We may consider the complete wetting to be carried out in stages so that the total heat evolved is the sum of such terms as $Q \delta R$ carried as far as saturation. The heat of wetting reckoned per grm. of dry material is therefore given by—

$$W = \tfrac{1}{100} \int_{R}^{R_s} Q dR \qquad . \quad . \quad . \quad . \quad . \quad (5)$$

where R_s is the saturation regain. We may, of course, take as the upper limit of the integral the value of R at which Q becomes inappreciable. On the regain-heat of absorption diagram, the heat of wetting per 100 grm. of

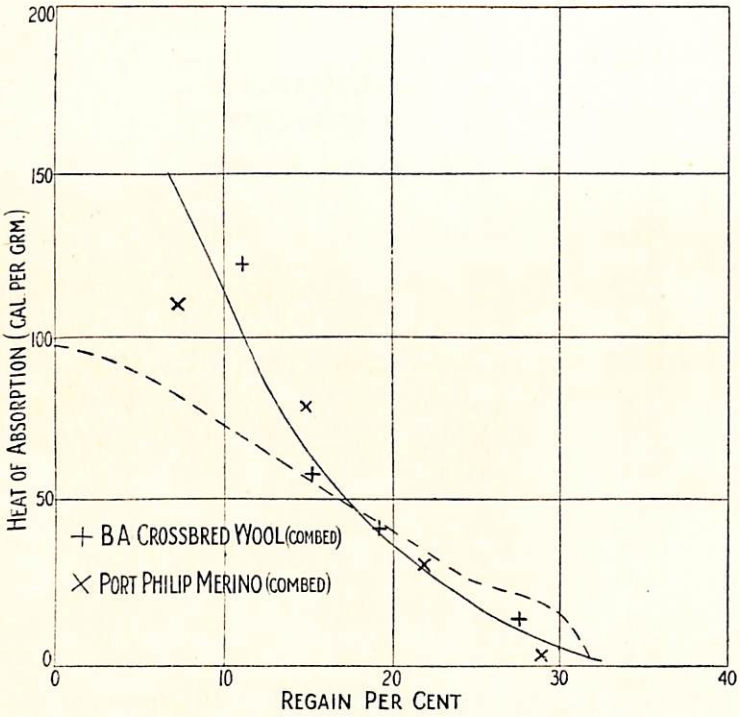

FIG. 2

dry material is represented by the area contained by the ordinate corresponding to the initial regain, the curve and the regain axis.

The integration is most readily performed by tabulating values of Q obtained from large scale versions of Fig. 1 and Fig. 2 for an equidistant series of values of R, starting with the lowest value at which Q may be assumed to be zero, and making use of the simple rule—

Area = interval × sum of all ordinates minus mean of extreme ordinates. Values of the heat of wetting of cotton and wool for integral values of R ranging from mean saturation to as near complete dryness as possible are given in Tables II. and III.

TABLE II.—Cotton

R	Q	ΣQ	$\int QdR$	W calories per grm.
20	0	0	0	·0
19	2	2	1	·0
18	4	6	4	·0
17	7	13	9	·1
16	10	23	18	·2
15	13	36	29	·3
14	16	52	44	·4
13	19	71	61	·6
12	22	93	82	·8
11	26	119	106	1·1
10	30	149	134	1·3
9	34	183	166	1·7
8	39	222	202	2·0
7	46	268	245	2·4
6	57	325	296	3·0
5	72	397	361	3·6
4	92	489	443	4·4
3	137	626	557	5·6

TABLE III.—Wool

R	Q	ΣQ	$\int QdR$	W calories per grm.
34	0	0	0	·0
33	1	1	0	·0
32	2	3	2	·0
31	3	6	4	·0
30	5	11	8	·1
29	7	18	14	·1
28	9	27	22	·2
27	11	38	32	·3
26	14	52	45	·5
25	17	69	60	·6
24	20	89	79	·8
23	23	112	100	1·0
22	27	139	125	1·3
21	31	170	151	1·5
20	36	206	188	1·9
19	41	247	226	2·3
18	48	295	271	2·7
17	55	350	322	3·2
16	62	412	381	3·8
15	69	481	446	4·5
14	77	558	519	5·2
13	85	643	600	6·0
12	95	738	690	6·9
11	104	842	790	7·9
10	114	956	899	9·0
9	124	1080	1018	10·2
8	134	1214	1147	11·5
7	146	1360	1287	12·9

The heat of wetting of cotton has been measured by Barratt and Lewis,[8] who find a value 3·6 cal. per grm. for cotton at an initial regain of 5·1%. It will be seen that this value is in excellent agreement with the value calculated in Table II.

We may say that Schloesing's experimental results pass very satisfactorily the test which the application of the above thermodynamical reasoning forms. We will now apply the same test to Hartshorne's data.

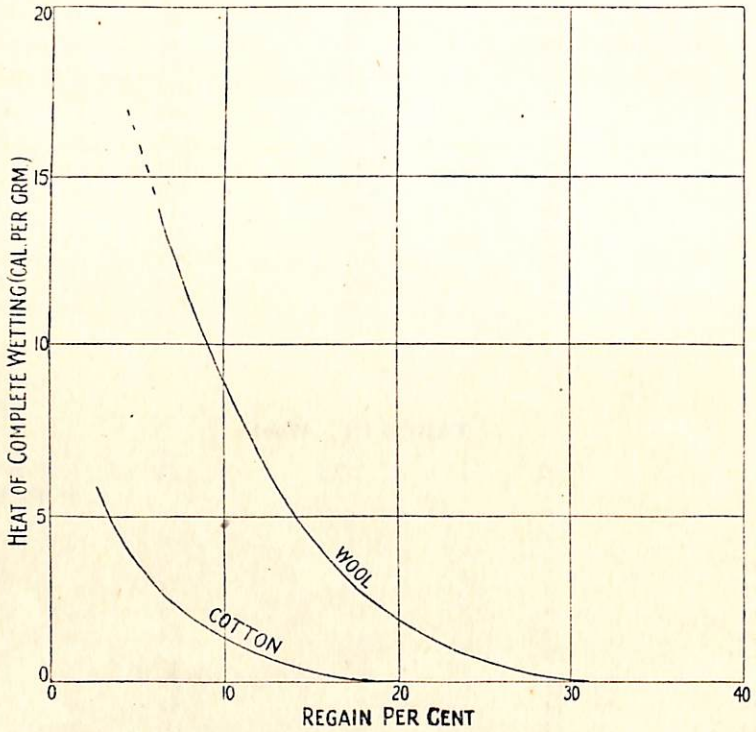

FIG. 3

Hartshorne gives tables for the regain of cotton and wool as a function of the relative humidity and temperature. These tables have been calculated by first obtaining an empirical formula of the type—

$$y^2 - axy - bx^2 - cy + ex = 0 \qquad . \quad . \quad . \quad . \quad . \quad (6)$$

where $x = R$ and $y = \frac{H}{R}$, for a single temperature (70° F.), and then calculating the values for other temperatures by means of the two following laws—

For cotton—"For the same humidity the first powers of the regain at different temperatures are to each other inversely as the first powers of the corresponding temperatures."

For wool (worsted yarn)—"For the same humidity the squares of the regains at different temperatures are to each other inversely as the cubes of the corresponding absolute temperatures."

The direct application of equation (4) is rather inconvenient owing to the form of the tables. We may, however, readily obtain a more convenient formula. We have—

$$\left(\frac{dH}{dT}\right)_R = -\left(\frac{dH}{dR}\right)_T \left(\frac{dR}{dT}\right)_H$$

and

$$R = KT^{-n},$$

where K is a function of the humidity only, and where for cotton $n=1$ and for wool $n=3/2$. Hence we have

$$Q = n\rho T \frac{d \log H}{d \log R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

By means of this equation the values of Q may be calculated quite readily from Hartshorne's tables. When R is small, equation (6) becomes

$$cH = eR^2$$

so that

$$\frac{d \log H}{d \log R} = 2$$

and

$$Q = 2n\rho T$$

or

$$Q = 3\rho T \text{ for wool}$$

and

$$Q = 2\rho T \text{ for cotton}$$

so that in the neighbourhood of zero regain the heat of absorption becomes at 75° F. 98 cal. per grm. for wool and 65 cal. per grm. for cotton.

Curves constructed from Hartshorne's data* are shown alongside the corresponding curves from Schloesing's data. It will be seen that they differ markedly from the Schloesing curves. They do not show the great increase of slope in the neighbourhood of zero regain which one would expect on theoretical grounds. We must therefore conclude that the two "laws of regain" quoted above cannot be true.

The paucity of vital experimental details in Hartshorne's paper makes it difficult to account for the fact that he does not find the marked increase in the value of $(d \log H/dT)_R$ at low regains which Schloesing finds. Hartshorne gives experimental details in support of his laws at one humidity, and simply states that the laws are confirmed experimentally at other humidities. Hartshorne's method of obtaining an empirical equation between H and R (which he erroneously calls a "law of regain") from four pairs of values and two tacit assumptions as to the value of dH/dR at $R=0$ and at saturation is, of course, thoroughly unscientific (the correct method is to calculate the constants from a large number of pairs of values by some averaging method, such as the method of least squares or that of zero sum[10]), but it does not explain the discrepancy. The most probable explanation is Hartshorne's neglect to take any account of the variation with temperature of the relative humidity corresponding to a given concentration of sulphuric acid. Sulphuric acid, like wool, has a marked heat of water absorption, so that a given concentration of acid gives a higher humidity the higher the temperature. If the heats of absorption were the same for

*The broken lines in Fig. 1 and Fig. 2

wool and the acid at mutually equilibrating water contents, the assumption that the acid gives the same relative humidity at all temperatures would lead to the conclusion that the regain of wool is independent of the temperature (as stated by Trouton). Actually, however, the heat of absorption of water by wool is the greater (except perhaps at very low humidities), so that in spite of such an assumption the humidity corresponding to a given regain will still appear to increase with temperature though at a diminished rate.

As an example of the magnitude of the error produced in this way, let us consider the example given in Hartshorne's paper. At a supposed 55·6% humidity produced by a 40·5% solution of acid, the regain is 15·39% at 40° F. and 13·00 at 100° F. Now according to R. E. Wilson's[11] curve the percentage humidity increases 8 for 75° C. rise of temperature. This corresponds to about 3·5 for 60° F. (100°–40°). This 3·5 corresponds, according to Hartshorne's tables, to an increase of ·74 in the regain. Hence the difference 2·39 (15·39–13·00) which Hartshorne gets for the effect of a change of temperature of 60° F. at a humidity of 55·6% should be greater by approximately ·74, *i.e.* it should be 3·1.

In conclusion, it may be pointed out that the thermodynamical reasoning contained in this paper involves the assumption that we are dealing with a true reversible equilibrium. It is known that there are considerable hysteresis effects when textile materials are taken through cycles including extremes of treatment, but whether there is any appreciable hysteresis in cycles of small range, seems to be an open question. Only this latter type of hysteresis would affect the validity of our theory.

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